

“DEPHOSPHORIZATION OF STEEL PRODUCED FROM SPONGE IRON IN THE INDUCTION FURNACE”

Thesis submitted in partial fulfillment of the requirements for the award of the degree of

Master of Technology

in

Mechanical Engineering

Submitted by

ABHILASH PUROHIT

Roll No.-**212MM2458**

[Specialization: Steel Technology]



Department of Metallurgical and Materials Engineering

National Institute of Technology

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CERTIFICATE

This is to certify that the thesis entitled, “**DEPHOSPHORIZATION OF STEEL PRODUCED FROM SPONGE IRON IN THE INDUCTION FURNACE**” submitted by **Mr. ABHILASH PUROHIT** Roll No. 212MM2458 in partial fulfillment of the requirements for the award of Master of Technology Degree in Mechanical Engineering with specialization of Steel Technology at the National Institute of Technology, Rourkela, is an authentic work carried out by him under my supervision and guidance. To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/Institute for the award of any Degree or Diploma.

Prof. U.K. Mohanty

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ABSTRACT

A certain proportion of DRI produced in India is consumed for the steel production through the induction furnace route which provides for slag metal separation actuated by a mere melting of the DRI without any purification reactions. Government of India, owing to the poor quality of steel produced from DRI through the induction furnace route has stipulated that, steel to be marketed must contain less than 0.085% of combined sulphur and phosphorous. Therefore the DRI producing companies are initiating a method of dephosphorizing the steel produced from the induction furnace route. The present work is an attempt at dephosphorizing the steel produced in the induction furnace route from DRI which is high in phosphorous (upto 0.096% are common). A neutral lining is provided in the induction furnace and double slagging by the addition of Calcium Aluminate, Calcium Barium Aluminate and Barium Aluminate is adopted. It is observed that double slagging by the addition of Barium Aluminate yielded the best result so far as the dephosphorization is concern.

Keywords: Induction furnace route, Dephosphorization, Synthetic slag, Neutral lining, Double slagging.

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Chapter-1

INTRODUCTION

1.1. Introduction:

Steel making in India is branched into two sections specifically primary route and secondary route. In the primary route of steel making iron ore is used as raw material. In the first stage iron ore is melted in a blast furnace to produce hot metal, and in second stage this hot metal is moved to a steel making shop to produce steel in a basic oxygen furnace. In the secondary route of steel making steel is produced using sponge iron, scrap etc. In this route steel is produced in electric furnaces.

The main electric furnaces that are used in secondary steelmaking to produce steel are induction furnace and electric arc furnace. As per the information presented by ministry of steel, total manufacturing of crude steel in India is around 74MT in the last year. Out of this 35 percent steel was produced using induction furnace. The prime raw material for induction furnace is steel scrap, sponge iron and cast iron. The percentage of directly reduced iron in the burden differs from 10 to 95 percent, depending on its inventory and monetary value of manufacturing. Large scale of steel formed through secondary route is alloy steel and plain carbon steel. [2]

In the present work, our objective is to set up preliminary info for dephosphorization of steel in 150 kg induction furnace. As for the expulsion of phosphorous basic environment is desirable, the basicity is controlled by the addition of Barium Aluminate, Calcium Aluminate and Calcium Barium Aluminate in the form of slag. The FeO present in DRI is responsible for providing oxidation potential to the added slag. Three heats had been carried out for each slag and, slag and metal samples were collected to determine the degree of dephosphorization.

Phosphorous comes to induction furnace from DRI and pig iron and the quality of pig iron depends on the quality of hematite. The range of phosphorous varies from 0.05 to 0.09 % with the variation in the quality of raw materials. Steel containing phosphorous has some adverse effect on the quality of steel, hence the amount of phosphorous should be beneath a suitable amount. The elimination of phosphorous from steel is conducted by oxidation. The compound which is produced after oxidation reaction is in the form of P_2O_5 , which is a component of the dross. Dephosphorization is very much sensitive towards the operating temperature of the furnace. Because at very high temperature phosphorous in the dross may get back to the steel.

On the primary route of steel making oxidation potential for removal of phosphorous is obtained by direct lancing of the oxygen jet into the bath. But in induction furnace route it is difficult to remove phosphorous by oxygen lancing because, here the height of metal level is equal to the depth of furnace. The second constraint that suppresses dephosphorization is the acidic refractory lining which is used in induction furnaces. The removal of phosphorous and sulfur is difficult with acidic lining as they form basic slag. In the present work we had used Magnesia based basic lining for the removal of phosphorous. [13, 14]

1.2. Purpose of the project:

- a) Dephosphorization of steel.
- b) Optimization of raw material chemistry.
- c) To increase the yield of the process

Objective 1 High productivity with better quality

Action plan Induction furnace making quality steel by Dephosphorization

Objective 2 To improve yield.

Action plan..... Reduce slag FeO% with carbon.

Chapter-2

LITERATURE SURVEY

2.1. Introduction:

The estimate for the development of induction furnace starts, when the principle of electromagnetic induction was discovered by Michael Faraday. Then first experiment on induction furnace was started by De Ferrant in 1870. In 1890 the first induction furnace was patented by Edward Allen for melting metal. [6]

There are two basic laws of electricity:

- a) The first is that a current flowing through a conductor will bring forth a magnetic field around that conductor. If this wire is wound into a cylindrical coil, the magnetic field of each turn is added producing an intensified magnetic field. The field is related to the amount and direction of the current. The field is maximum when the current is maximum and will reverse direction if the current reverses direction.
- b) The second fundamental is related to Faraday's Law, which says that when a flux which links a coil is changing, there is an electro-motive force (emf) induced in the coil. If these flux linkages change in a closed electric circuit, the emf produced causes a current to flow. A solid metallic block will produce currents swirling around in eddies in a plane perpendicular to the flux. These eddy currents produce the I^2R losses which generate the heat required. Proper selection of coil frequency and power density allows for the practical application of induction heating and melting.

2.2. Effect of phosphorus on the properties of steels:

Steel containing phosphorous has some adverse as well as good effects. Phosphorous has great influence towards the solid solution strengthening of ferrite. The comportment of a modest quantity of phosphorous can increase the yield and ultimate strength of mild steel. It also increases the deep drawability and hardness of steel. Referable to the above advantages such steels are used for cold forming operation. Phosphorous in steel can also increase corrosion resistance and metal cutting characteristic. [4]

On the other hand the harmful effects of phosphorous in steel include various types of embrittlement, which reduce the resilience and malleability. High phosphorous steel melt has low melting point film, which produces crack during continuous casting.

2.2.1. Cold shortness in steel:

The brittle behavior of steel containing phosphorous, at a temperature less than recrystallization temperature is called cold shortness. It is a condition of wrought iron, steel, or other metal, in which the metal, on account of its brittleness, cannot be worked when cold without fracture or cracking at the edges. Phosphorous decreases ductility and hence increase the tendency of the steel to produce crack during cold working.

2.2.2. Effect of phosphorous on ductility:

When Phosphorous, Manganese or Silicon is added to steel, the tensile strength of steel increases and elongation decreases. This relationship is shown in Figure 2.1. A balance between cold formability and hardness must be maintained to produce high strength formable steel. As Phosphorous level increases, ductility of steel decreases severely due to the embrittlement.

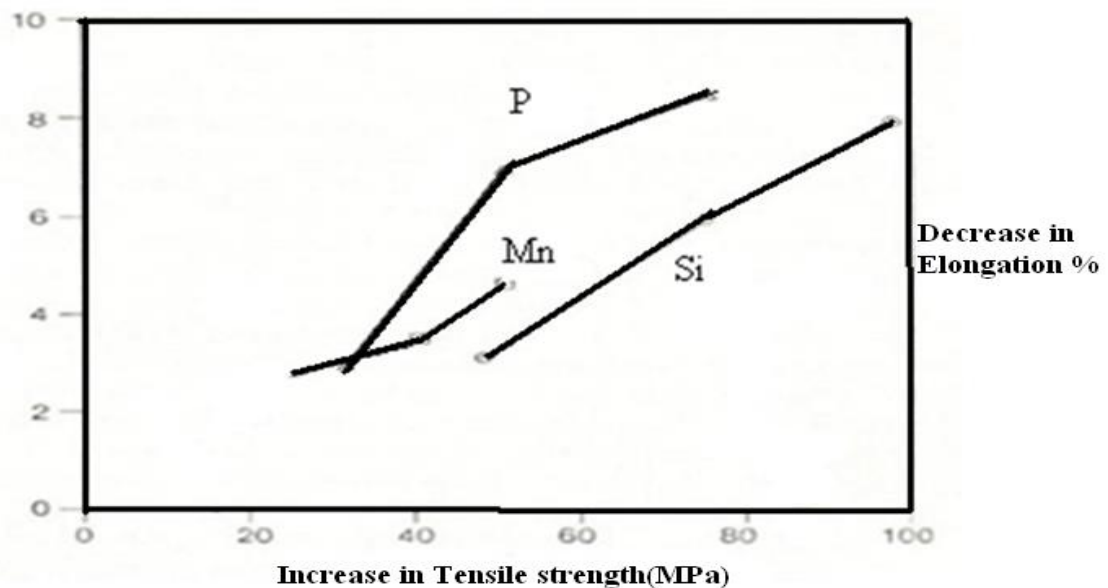


Figure 2.1. Relationship between decrease in elongation with increase in tensile strength

2.2.3. Effect of phosphorous on strength:

Figure 2.2 show the change in lower yield point as a function of alloy addition. From the Figure 2.2 we can conclude that, small amount of phosphorous can increase yield point by a large amount. Only Carbon and Nitrogen have a higher strengthening effect than phosphorous. This is because, phosphorous is substitutional solute in ferrite, where as Carbon and Nitrogen enter the crystal lattice as an interstitial solute.

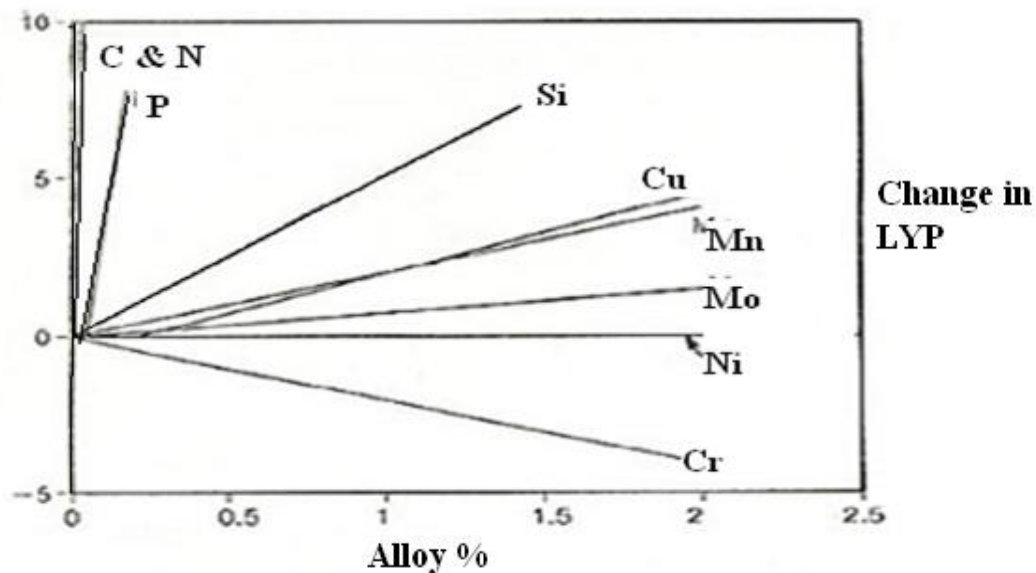


Figure 2.2. Effect of different elements on yield point of steel.

2.3. Sources of phosphorous input:

Phosphorous comes in to steelmaking furnace from:

- Hot Metal

All the phosphorous present in blast furnace burden goes to hot metal, since dephosphorization is not possible in blast furnace due to reducing atmosphere.

- Sponge iron

Sponge iron may contain upto 1.0% phosphorous.

- Recycled BOF Slag
- Coke

2.4. Requirement of Low phosphorus Steels:

- To have improved mechanical properties like temper embrittlement, low temperature ductility etc.
- To have better corrosion resistance and deep drawing properties
- To reduce hydrogen induced cracking and stress corrosion cracking
- To reduce chances of cracking during bending
- For the equipment in chemical industry
- For reprocessing equipment of the nuclear industry
- To prevent segregation during continuous casting.

2.5. Phosphorous Reaction:

2.5.1. Kinetics and Thermodynamics of phosphorous removal:

Although the boiling point of phosphorous is very low a considerable amount of it still dissolved in liquid iron because of its strong interaction parameter with iron. The iron and phosphorous lines on the Ellingham diagram are so closed to each other that the entire phosphorous in the burden gets reduced along with iron in an iron blast furnace. This might have posed a serious problem in the oxidation of phosphorous but for the fact that the two lines are widely separated during steel making by decreasing the activity of P_2O_5 using a strong and excess basic flux. The standard and non-standard lines on the Ellingham diagram are shown in Figure 2.3. The steelmaking slag may contain upto 25% P_2O_5 but even then the activity of P_2O_5 in slag remains extremely low. For effective removal of phosphorous basic steelmaking process have to employ slags of high basicities. If the basicity falls, phosphorous may revert back to the metal phase. In acid steel making process since the slag is nearly saturated with silica, phosphorous can not be eliminated at all. [7]

The oxide Ellingham diagram of interest in refining basic pig iron. Decreasing the activity of the product oxide results in rotation of the line in clockwise direction. By employing highly basic slags, the iron and phosphorous lines are thus widely separated. The shaded area in Figure 2.3 indicates the basic steel making condition. [17]

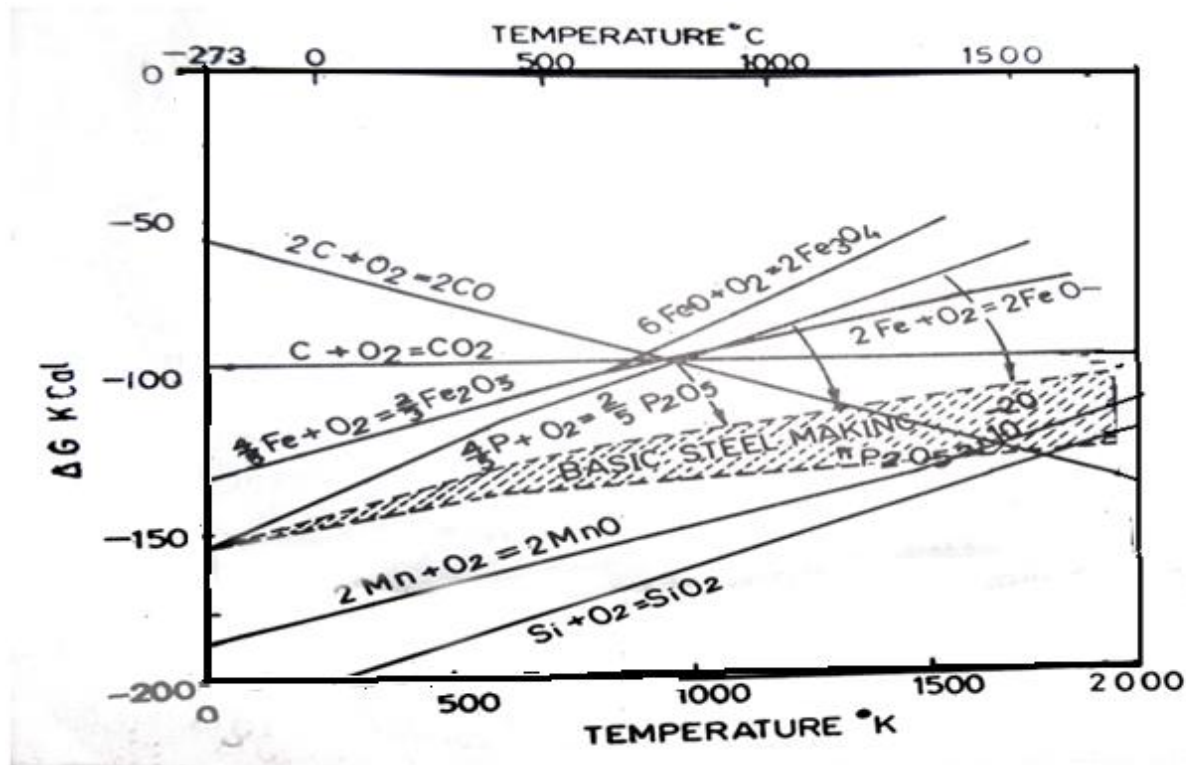
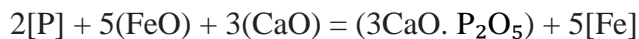


Figure 2.3. Ellingham diagram.

The partitioning of phosphorous between slag and metal can be given as:



And the equilibrium constant is:

$$K = \frac{a(3CaO \cdot P_2O_5) \cdot a^5[Fe]}{a^2[P] \cdot a^5(FeO) \cdot a^3(CaO)}$$

The ratio of phosphorous content in slag to that in metal is generally referred to as phosphorous partition coefficient D_p which has a higher value for higher basicity and higher oxidizing power of the slag.

The activity function for phosphorous distribution between slag and metal as obtained by Flood is:

$$\log K = 21N'(Ca^{2+}) + 18N'(Mg^{2+}) + 13N'(Mn^{2+}) + 12N'(Fe^{2+}) + \dots$$

That is the dephosphorizing ability of various basic oxide is in the ratio of,

$$\begin{array}{cccc}
 \text{Ca} & : & \text{Mg} & : & \text{Mn} & : & \text{Fe} \\
 10^{21} & : & 10^{18} & : & 10^{13} & : & 10^{12} \\
 30,000 & : & 1000 & : & 3 & : & 1
 \end{array}$$

In other words lime is 30 times more effective on molar basis and 20 times more effective on weight basis for dephosphorization than magnesia. The FeO is only effective as an oxidizing agent and not as a base. Of course, Na_2O , BaO are more powerful than CaO , but they cannot be used in steel making owing to their tendency to attack the lining of the furnace. The inter-relationship of partition coefficient, basicity and FeO content found in laboratory experiments are shown in Figure 2.4 and Figure 2.5. The partition coefficient increases with increase FeO content upto 15% because of its high oxidizing ability. If FeO content increase beyond a certain limit, the ratio of lime is decreased and hence the advantage of high oxidizing ability of FeO is neutralized by the loss of time in the slag resulting in a maximum partition coefficient at around 15% FeO. Increase in temperature tends to lower the value of partition coefficient and vice-versa and hence dephosphorization is more effective at low temperature.

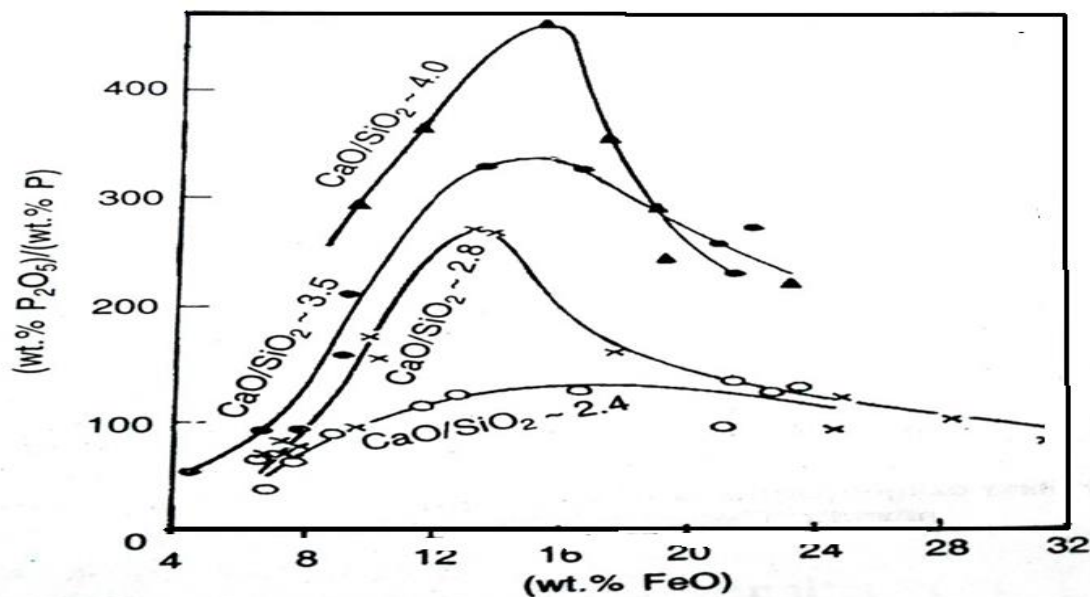


Figure 2.4. Dependence of distribution ratio, on the FeO content of slag

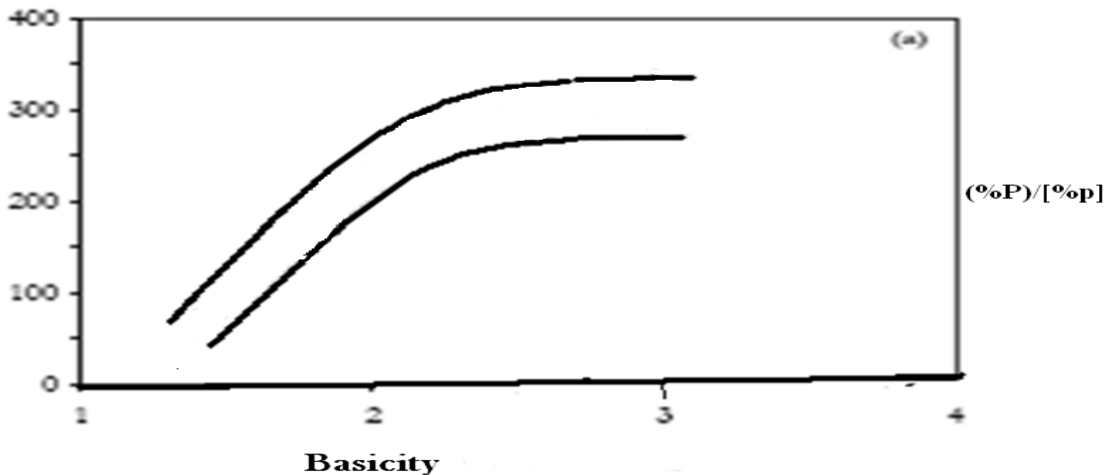


Figure 2.5. Influence of Basicity on equilibrium Partition ratio.

Soda ash is 100 times superior to lime, on molar basis, for dephosphorization, but its use in practice is forbidden because of its severe corrosive action on furnace refractories. Usually the magnesia content of basic steel making slag is not under control because it reaches equilibrium with furnace lining. The steelmaking is, therefore, left with the control on lime, silica and iron oxide content of the slag to effect required dephosphorization of the melt.

Since phosphorous oxidation is highly exothermic reaction it is favored by lower temperature. Excessively high temperature, risen in the course of refining, may lead to reversion of phosphorous from slag to metal during steel making in actual practice. [7]

2.6. Need for low phosphorous steels:

- Causes hot shortness and temper embrittlement.
- Ductility and strength goes down if phosphorous is very high.
- Essential when want to have excellent mechanical properties (Ductility, Toughness and Strength).
- For special applications (Automobiles EDD Applications $[P] < 0.010$).
- Increasing proportion of continuous cast heats where high temperature at end point is not favorable for dephosphorisation.
- High phosphorous heats cause more breakouts in continuous casting due to formation of low melting point film.

2.7. Induction furnace steelmaking:

A melting furnace in which electric current is applied to melt metal is called induction furnace. Melting and alloying a wide variety of metals with minimum melt loss are the features of induction furnace. Induction furnace is also used for refining of metal. [6]

Straight off a day's induction furnace making has come forth as a major steel producing operation. In India induction furnace plants are termed as mini steel plants, because the maximum production capacity of these plants is less than 1MT of steel per year. In induction furnace, steel scrap is used as charge material, only due to less availability of steel scrap directly reduced iron (DRI) is likewise utilized in induction furnace. Now a days induction furnace in integrated with mini blast furnace, and in such type of plants the metallic charge, usually consists of hot metal, steel scrap and DRI in varying proportions to get different properties of steel. Improvement of induction furnace design goes on day by day, which permits enhancement of electrical efficiency in modern furnaces, and metallurgical efficiency has also been greatly improved by oxygen lancing.

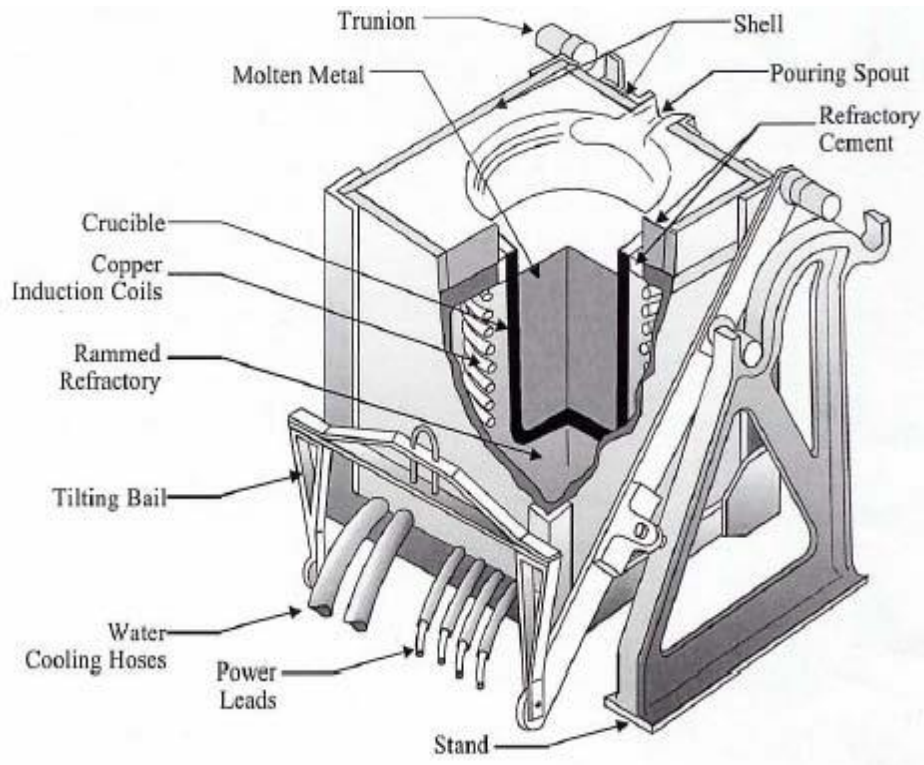


Figure 2.6. Schematic of induction furnace

2.8. Types of induction furnace:

There are basically two designs of induction furnaces are available, namely, the core type or channel furnace and the coreless type. Both types have advantages which make one or the other suitable to a particular operation. As compared to coreless induction furnace, core type furnace is a more efficient type of induction furnace. In case of core type construction maximum power transfer into the metal is possible. This design has a distinct advantage of providing a large capacity of molten metal with low holding power level. Core type induction furnace is an excellent furnace for small foundries with special requirements for large castings. Because of the requirement to keep the channel molten, core type furnaces are energized 24 hours a day. Hence the application of core type furnace is limited to one alloy or similar base alloy. Hence the power supplies are of line frequencies of 60 or 50 Hz. If quick melting of one alloy is desirable, then coreless induction furnace is used. The coreless furnace can be used for one shift operation because it is easy to stop and restart the furnace. [6]

Coreless induction furnace process has some advantages over other types of arc furnace.

- i. Since there are no electrodes, it is possible to melt steels very low in carbon.
- ii. The metal produced is really low in gases because of the absence of arc.
- iii. Temperature control of the process can be managed easily.

The disadvantages of induction furnace are:

- i. Life of basic lining is low.
- ii. Low temperature of slag, which is heated from the metal.

2.9. Devices for Electric heating:

Any material through which an electric current flows is heated thereby. The rate at which heat is generated depends on current density and the specific resistance of the material which is called as a 'resistor'. [11]

Electric energy can be utilized for industrial heating in several ways.

- a) The material to be heated serves as a resistor.

- b) Separate resistors transfer heat to the work load by radiation and convection and in a few cases by conduction.
- c) The work load is heated by induced current.

2.10. Principle of induction furnace:

The principle of induction furnace is the induction heating.

2.10.1. Induction Heating:

A change in the electric current that flows in a wire causes a change in the magnetic conditions around the wire. The change in magnetism can be used to produce an electric current in a properly placed object, which is heated by the current. The general equipment required for induction heating consists of a coil of wire in which alternating current flows. The object to be heated is placed inside the coil of wire. Factor affecting distribution of temperature in the heated object is the frequency of alternation (cycles per second).

At a high frequency, temperature at the skin of the work piece is highest. The rate of heating decreases exponentially and rapidly towards the center. At low frequency also distribution of temperature from skin to the center is exponential, but temperature decreases more gradually than it drops with high frequency. This is the facts; bars of large cross section are heated with low frequency. [11]

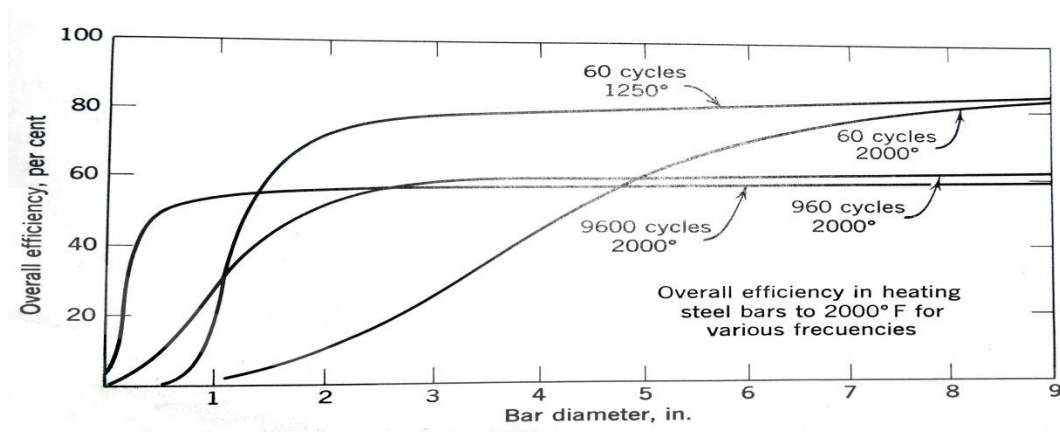


Figure 2.7. Effect of frequency and bar diameter on efficiency of induction heating of steel bar to 2000F.

Induction coils are not expensive, but additional equipment required for induction heating is expensive. Low frequency (60cps) heating requires more capacitors for correction of the power factor.

2.11. Construction and Working:

There are two types of furnaces namely combustion furnace and induction furnace. They produce heat in two different manners. The furnace in which heat is produced by burning a fuel like natural gas, coal, etc. is called combustion furnaces (heat required for melting of the charge material is obtained by burning of the fuel). But in induction furnaces, heat generated is not by combustion.

Alternating current from a power supply flows into a furnace and through a coil which is built up of hollow copper tubing. Due to this an electromagnetic field is created which passes through the refractory lining and couples with conductive metal charge inside the furnace. Then an electric current flows inside the metal charge, generating heat, which causes metal to melt. [15]

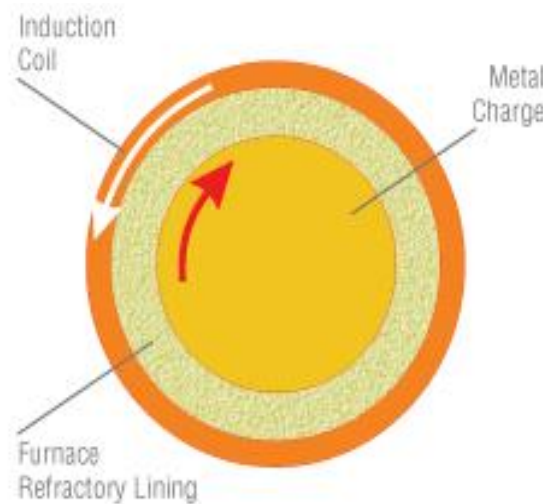


Figure 2.8. Directions of current in induction coil and metal bath.

2.12. Electrodynamics phenomena in coreless induction furnace:

In a coreless induction furnaces there are two concentric conductors. The inductor works as external conductor and the molten metal, the internal one. In these conductors current flows in the opposite direction, and they repel each other. As the inductor is a rigid conductor, it remains

fixed, while the molten metal moves from the wall of the furnace towards the axis of the crucible.

The magnetic flux extends horizontally over the metal surface, after it passes from the annular gap between the two conductors. The horizontal component of the magnetic field produces electrodynamic forces which act perpendicular to the surface of the metal that is upwards at the bottom and downwards at the top surface of the metal. Force is maximum at the wall of the furnace.

This combined effect of horizontal and vertical forces causes the metal to circulate and forms a convex metal surface. An advantage of this phenomenon is that the metal is stirred, which equalizes its temperature and composition and speeds up melting, but the convex portion of the metal is thus exposed, since the slag flows towards the walls. It is possible to cover the meniscus by increasing the bulk of slag, but this may have an adverse effect on the lining.

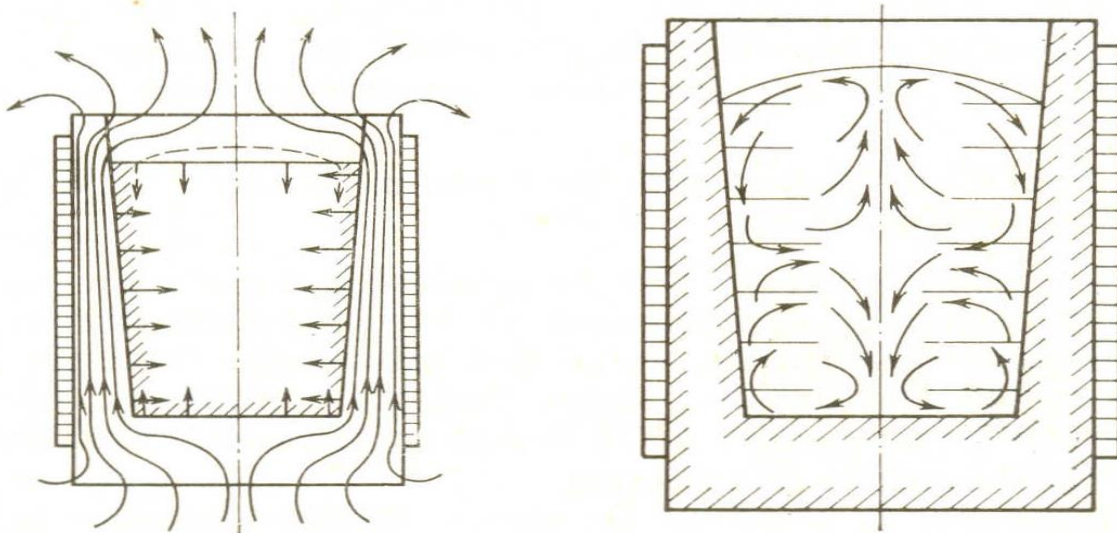


Figure 2.9. Electrodynamic circulation of metal in the induction furnace:

2.13. Advantages of induction furnace over electric arc furnace:

Induction furnace consumes less power compared to EAF due to faster melting, lower tapping temperature and higher power density. Melting of FeCr is difficult in an arc furnace due to the

absence of stirring. Also, heat losses in EAF are high as lime and fluxes added to protect the lining take away substantial amount of heat.

In induction furnace no electrodes are used as in EAF thus reducing cost of production. Again it uses lesser quantity of refractory. Initial investment of plant and equipment is less. Acidic ramming mass used in induction furnace is much cheaper when compared to basic ramming mass and bricks used in EAF.

Induction furnace has lower tapping temperature compared to EAF to recover the oxidized chromium. Also there is no need to add reductants like carbon or FeSi in induction melting unlike in the EAF. Recovery of chromium is higher in induction furnace compared to EAF as negligible amount of chromium is oxidized in induction furnace. [5]

2.14. Manufacturing of DRI

2.14.1. Introduction

Direct reduction, an alternative route of iron making, overcomes some of the conventional blast furnace. Direct reduced iron (DRI) which is also known as sponge iron is manufactured through either natural gas or coal based technology. Oxygen from the iron ore escapes during the solid state reduction and leaves pores. When observed under the microscope, this looks similar to sponge, hence the name sponge iron.

Iron ore is reduced in solid state at 700°C to 1050°C either by reducing gas (H+CO) or coal. The investment and operating costs of direct reduction plant are low compared to blast furnace which requires coking coal for producing coke. Demand for use of DRI in steel making is increasing due to shortage of steel scrap and power.

The principal constituents of sponge iron are metallic iron, residual iron oxides, carbon and impurities such as phosphorous, Sulphur, Silica, Aluminum etc.

Micro structure of sponge iron looks as follows:

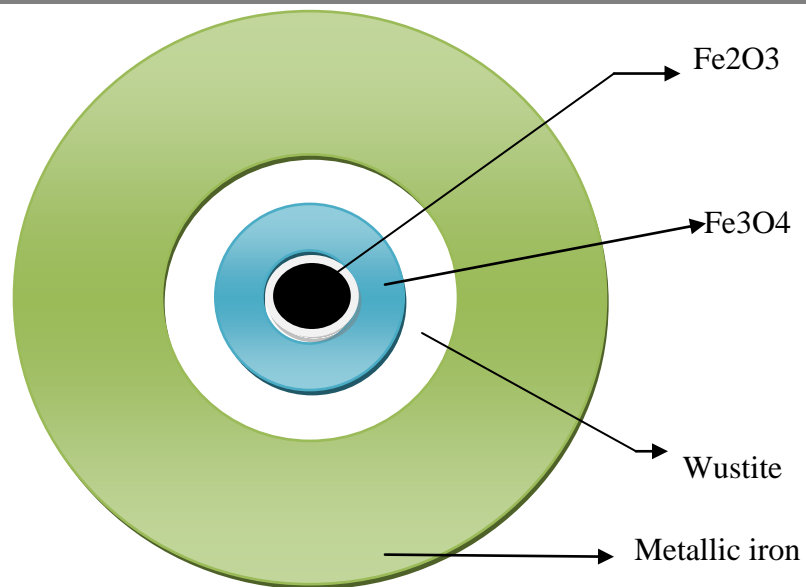


Figure 2.10: Microstructure of sponge iron

2.14.2. Characteristics of DRI

DRI can be produced in different forms, namely pellet, lump and hot briquette. The secondary product form from fine DRI is called cold briquetted iron. Hot briquette is also known as hot briquetted iron (HBI). Hot briquetted iron is a mixed solid form of pellet and lump which is pressed as 800 to 7000C immediately after reduction. Quality of hot briquetted iron can be varied by mixing lumps and pellets in different ratios. Due to high density and low surface area of hot briquetted iron, there is a low chance of.

Oxygen present in the DRI is in the form of FeO, which reacts eagerly with carbon in the molten bath and improves heat transfer, slag metal contact and homogeneity of the bath. DRI having higher Carbon content is desirable. Hence, gas based DRI (which content 1.0 to 2.5% C) is more desirable than coal based DRI (0.2% C). Depending on the process used for DRI production, the degree of metallization varies from 80 to 95%. Low degree of metallization leads to higher dross volume, more power consumption, increased heat time and low yield during steel making. [3, 16]

2.14.3. Types of sponge iron making:

- A. Coal based processes using rotary kiln.
- B. Coal based processes using shaft furnace.

C. Retort processes using gas or coal as the reluctant.

Rotary kiln:

Rotary kiln is reactor for sponge iron making, but it is also used for calcinations of lime stone, production of cement and manufacturing of refractory material. Because of its versatile usage in processing materials, it is used for drying, heating, calcining, sintering and reduction.

Normally the coal based rotary kiln method of making sponge iron is followed by the plants. Rotary kiln is like a closed vessel. The vessel body is container of uniform cylindrical shape. Its charging end is open for discharging gas and feeding raw materials. The other end is used for discharging of product and gangue material. The vessel body (shell) is made of boiler quality steel. The shell is protected by an inside layer of high alumina refractory, which takes care of the high operating temperature of 1000-1100°C. The kiln rotates at a constant speed with the help of gears and motors arrangement supported by rollers. Each kiln has seven zones, and each zone having blowers for supplying atmospheric air inside the kiln for burning of coal. Thermocouples are arranged in different zones to measure the operation temperature. [5]

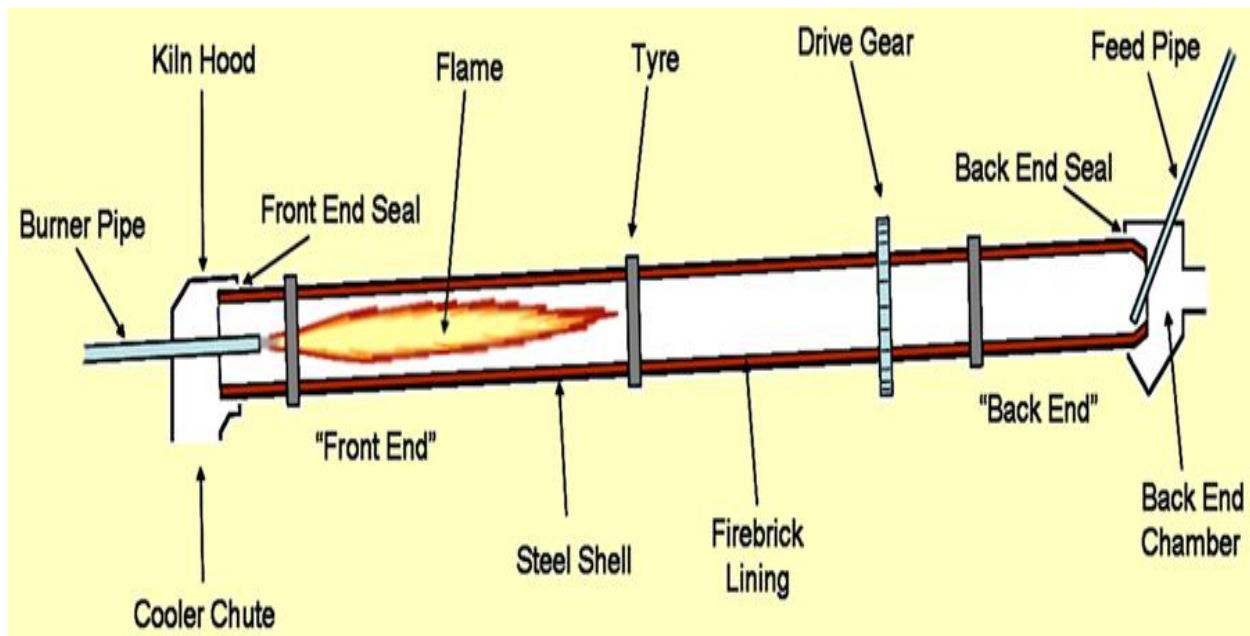


Figure 2.11: Rotary kiln terminology.

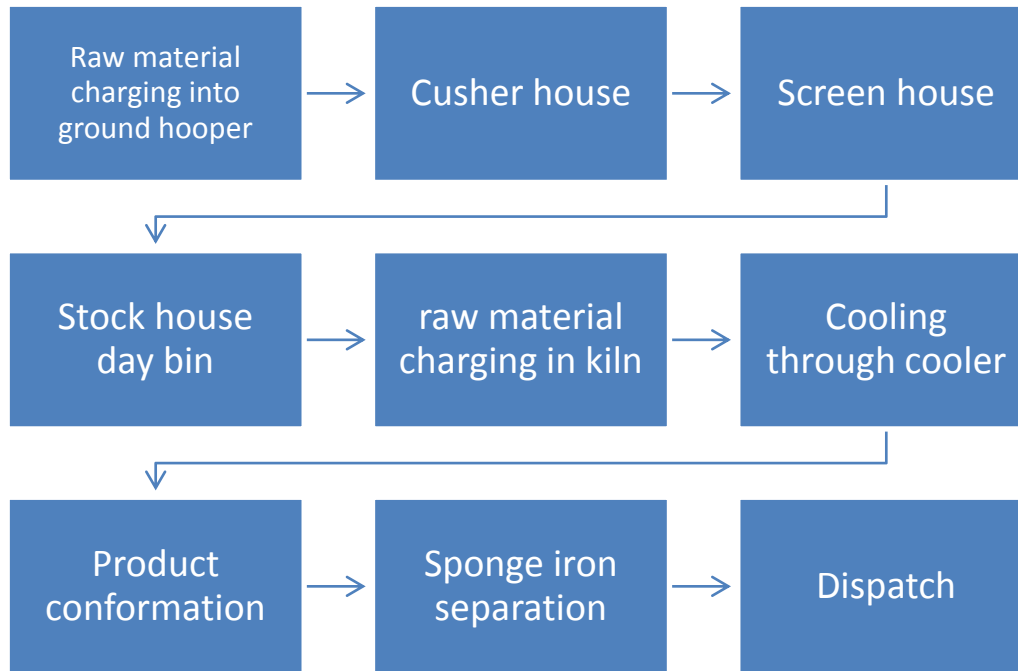
Table 2.1: Typical composition of iron ore.

Elements	Percentage (%)
Fe (Total)	62
SiO ₂	3.5
Sulphur	0.01
Al ₂ O ₃	4
Phosphorous	0.04
Loss of ignition	5
Tumbler index	85

Table 2.2: Typical composition of coal used for production of sponge iron.

Elements	Percentage (%)
Ash	32-35
Volatile matter	30-35
Fixed carbon	35-42
Sulphur	0.6
Phosphorous	0.1 maximum
Moisture	10-15 maximum
Particle size	10-15mm maximum

Limestone and dolomite are used as flux for de-sulphurization in sponge iron making process, since removal of Sulphur in steel making is more expensive than sponge iron process.

2.14.4. Process flow chat for sponge iron production:**2.15. Major factors affecting dephosphorisation:**

The best conditions for phosphorous removal from liquid steel from a thermodynamic viewpoint can be summarized as: [8, 9]

- A high basic, lime rich slag.
- A satisfactory high level of oxidation of iron (FeO content).
- The lowest possible temperature.
- The lowest possible amount of undissolved free lime in slag.
- An increased metal slag interface.
- Droplet generation trajectory and residence time
- Blowing Regime (Lance Height vs. Flow rate)

2.16. Limitations of dephosphorization:

- Poor yield of steel due to reblows; iron loss,
- Loss in the lining life of the converter ,
- Loss due to poor recovery of ferroalloys,
- Reduced life of ladles,

- Diversion of grades due to uncertain oxygen content of steel.

2.17. Process flow diagram:

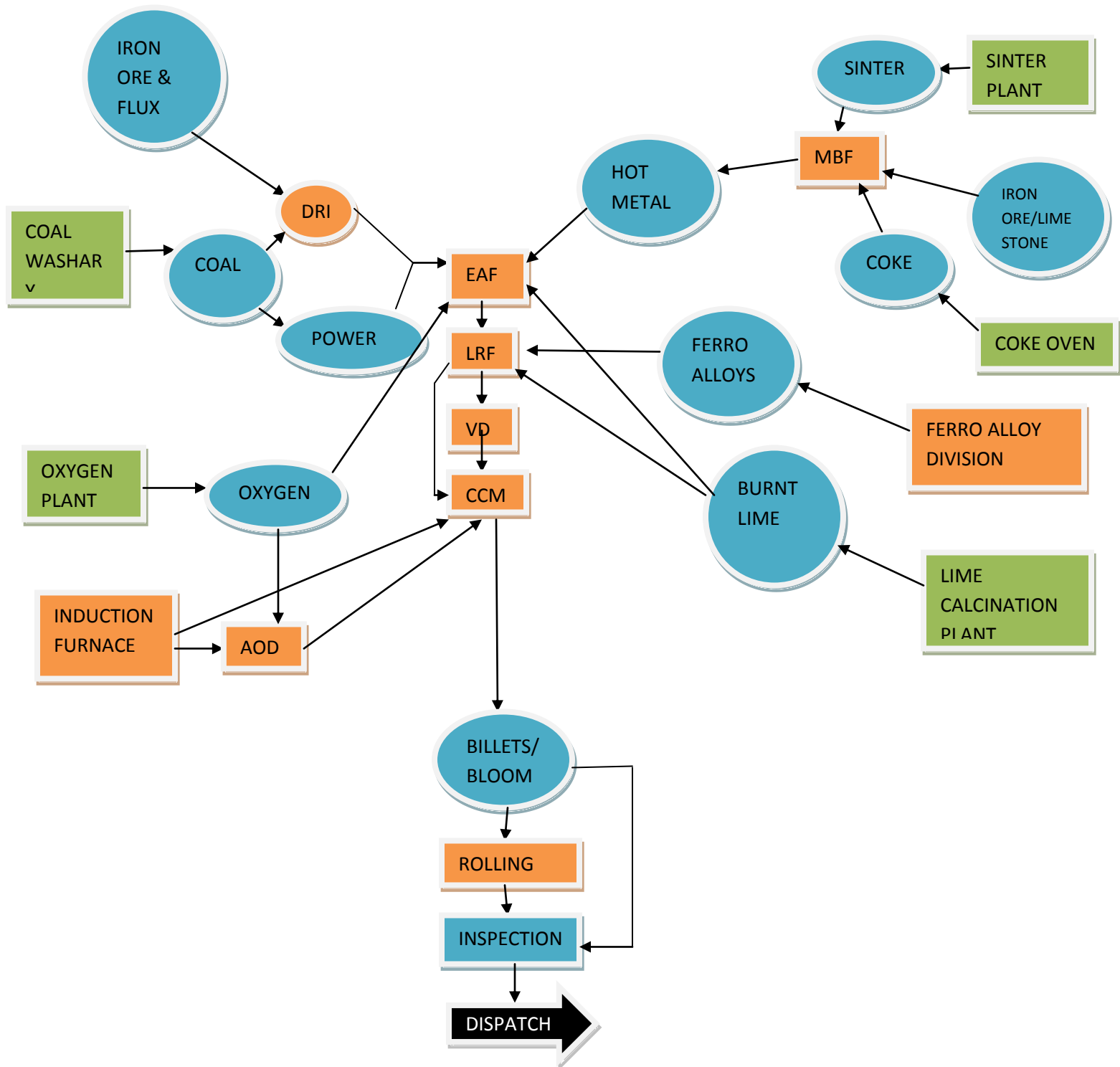


Fig. Process flow diagram

Chapter-3

EXPERIMENTAL APPARATUS

3.1. High Temperature Microscope:

3.1.1. Theory:

The heating microscope helps in determining characteristics of a sample, as prescribed in general industrial standard 51730.

The flow characteristic presented in terms of the characteristic temperature.

IDI: Initial deformation temperature

ST: Softening temperature

HT: Hemispherical temperature

FT: Flow temperature

Initial deformation temperature:

At this temperature rounding of edge of the curve occurs. The initial shape change indicates the beginning of sintering. The temperature helps us to determine surface thickness and thickness of the sample.

Softening temperature:

At this temperature outline of the sample changes. This is reported by the temperature at which specimen sinks by 1 division after IDT. It symbolizes the start of plastic deformation.

Hemispherical temperature:

At this temperature same is fused to a hemispherical shape. This is the melting point, according to German standards. It symbolizes sluggish flow of sample material.

Flow temperature:

At this temperature the sample liquefies, measured at 1/3 of height as measured at HT. It symbolizes liquid mobility of sample.

3.1.2. Procedure:

The sample was put on this furnace and heated initial temperature being the room temperature. Flow characteristics as presented in terms of four characteristics are observed.

Temperature at which first rounding of edge occurred, was noted as IDT. The temperature at which outline of specimen changed and it sank by 1 division after IDT was noted as ST. The temperature, at which the height of specimen was observed to be one third of its height at HT, was noted as FT.

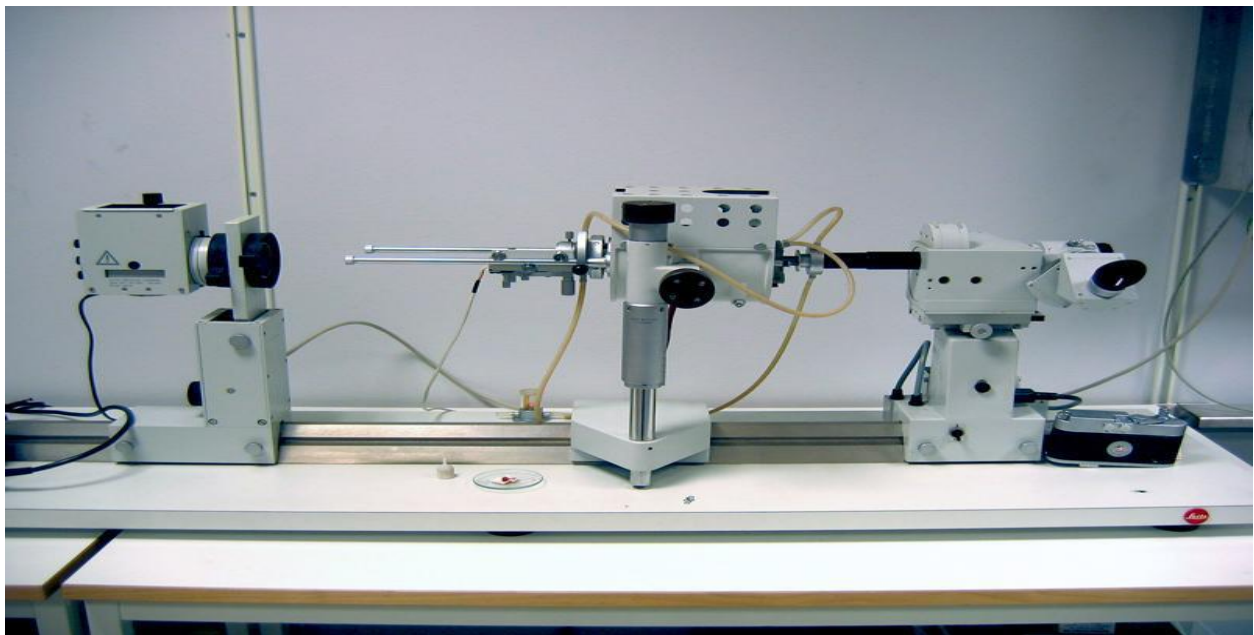


Figure 3.1: Pictorial view of Leitz heating microscope

3.1.3. Observations:

Table 3.1: Thermal characteristics of different synthetic slags.

Sample	Characteristic temperature			
	IDT in °C	ST in °C	HT in °C	FT in °C
Calcium Aluminate	1180	1287	1416	1467
Calcium Barium Aluminate	1243	1336	1481	1554
Barium Aluminate	1390	1410	1460	1549

3.1.4. Discussion:

- At ST, the height of the specimen decreased by 1 division from IDT.
- At HT, the height is the half of the base.
- At FT, the height was one third of the height at FT.
- The time taken by a sample to reach FT stage depends on sample that is, it varies from sample to sample.

High temperature microscopy required for improving heat furnace operation by the analysis, the temperature of surface stickiness of sample, that of plastic deformation flow of sample and liquid mobility can be obtained, on the basis of this, for a particular quality of material, various zones blast furnace or granular zone, cohesive zone, core active zone, stagnant zone and hearth can be adjusted.

3.2. Induction furnace:

Experiments for dephosphorization of steel in induction furnace were carried out in 150 Kg coreless type induction furnace of electrotherm Ltd. in Dalmia institute of scientific and industrial research (DISIR), Rajgangpur. The volume of the furnace was brought down to 40 Kg for easy manipulation. Alumina bricks with dry Al_2O_3 ramming mass were used as a lining.



Figure 3.2: Induction furnace used in the experiments.

3.2.1. Operational step:

Step-1	<ul style="list-style-type: none">• Close the hydraulic valve and tilt back the crucible in horizontal position.
Step-2	<ul style="list-style-type: none">• Do inspection of furnace.
Step-3	<ul style="list-style-type: none">• Charge the scrap as per standard charging sequence.
Step-4	<ul style="list-style-type: none">• Power on when the charging is done in the furnace.
Step-5	<ul style="list-style-type: none">• Do CPC addition as per requirement.
Step-6	<ul style="list-style-type: none">• Add required quantity of DRI as per charge mix with controlled feed rate.
Step-7	<ul style="list-style-type: none">• Increase the power input as per the feeding in the furnace.
Step-8	<ul style="list-style-type: none">• Do slag flushing parallel to the DRI feeding with the slag spoon.
Step-9	<ul style="list-style-type: none">• Sampling to achieve required carbon and phosphorus chemistry
Step-10	<ul style="list-style-type: none">• Achieve the tapping temperature (min 1670⁰ c).
Step-11	<ul style="list-style-type: none">• Just before tapping ensure that platform is clean & ladle is in position with purging.
Step-12	<ul style="list-style-type: none">• Ensure that purging is adjusted and addition of ferro-alloy & other material take place ladle is 2/3 full's

Table 3.2. Details of the high temperature induction furnace.

Maximum working temperature	1800°C
Diameter of furnace tube	20cm internal diameter
Depth of furnace tube	30cm
End cooling	Copper spiral for water circulation
Type of thermocouple	Pt-Rh type
Volume of furnace	9000cm ³
Frequency	1000Hz
Power	150KW

Chapter-4

EXPERIMENTAL SET UP

4.1. Experimental set up:

Laboratory scale experiments for dephosphorization of steel in induction furnace were carried out in 150 Kg coreless type induction furnace of electrotherm Ltd. in Dalmia institute of scientific and industrial research (DISIR), Rajgangpur. The volume of the furnace was brought down to 40 Kg for easy manipulation. Usually acidic lining is used in induction furnace but, here we had used neutral lining. Platinum Rhodium thermocouple was used to measure the operating temperature of the furnace. The raw materials used were mild steel rods (steel scrap) and sponge iron. The ratio of raw material was a 85% sponge iron and 15% steel scrap. The chemical composition of charge mix is given in table 4.1.

The furnace was dried after putting a mild steel rod and run the furnace at 10KW power for 1hour. Then 5kg mild steel was taken and melted at a power of 50KW. Initially the furnace was started with 10KW power supply and in each 10 min power was raised by 10KW up to 50KW. The frequency of the furnace was maintained in between 900 to 950 Hz. After complete melting 40kg sponge iron was added slowly. Total time taken for addition was 1hour. After complete addition of sponge iron temperature was measured. Then total slag was removed by spatula and temperature was measured 1630°C. Metal sample (metal sample 1) and slag sample (slag sample 2) was collected. Slag sample was taken out with the help of a spatula and metal sample was collected by tilting the furnace. Then 1500gm of Calcium Aluminate (mayanite) was added. The composition of Calcium Aluminate was 75% CaO and 25% Al₂O₃. Along with Calcium Aluminate 300gm of mill scale was also added in to the furnace. At this condition power was reduced to 35KW. Then again temperature was measured and it was around 1602°C. Total slag was removed and slag sample (slag sample 2) was collected. Metal had been removed and metal sample (metal sample 2) had been collected. Total metal had been removed from the furnace. Same experimental procedure had been followed for next two experiments where Calcium Barium Aluminate and Barium Aluminate were added as synthetic slag. The slag and metal samples for second and third heat were collected at 1607°C and 1610°C respectively



Figure 4.1. Melting of mid steel rod in induction furnace.

The sponge iron used in the experiments was provided by Odisha iron and steel Ltd (OISL), Rajgangpur. Chemical composition of sponge iron was determined by chemical analysis in OISL. Steel scrap analysis was done by spectrometer analysis. Before conducting the experiment three different slags were prepared namely Calcium Aluminate, Calcium Barium Aluminate and Barium Aluminate.

Table 4.1. Chemical composition of raw materials

<u>DRI</u>	%	<u>STEEL SCRAP</u>	%
Fe-M.....	78-80	C.....	0.22
Fe-T.....	87-90	S.....	0.045
P.....	0.096	P.....	0.075
S	0.03	Si.....	0.27
C.....	0.1	Mn.....	0.50
SiO ₂	2.404		



Figure 4.2. Neutral refractory lining



Figure 4.3. Prepared synthetic slags

Table 4.2. Chemical composition of prepared synthetic slag

NAME OF SLAG	CHEMICAL COMPOSITION
Calcium Aluminate	CaO – 75%, Al ₂ O ₃ - 25%
Calcium Barium Aluminate	CaO – 35%, Al ₂ O ₃ - 25%, BaO – 40%
Barium Aluminate	BaO – 75%, Al ₂ O ₃ - 25%

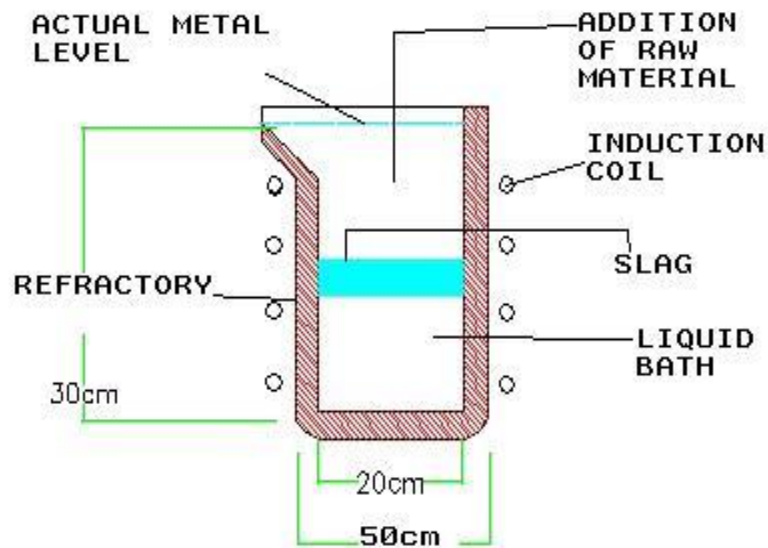


Figure 4.4. Line diagram of induction furnace.

Line diagram of coreless induction furnace used in the experiments is given in Figure 4.4. It shows the various dimensions along with different parts of induction furnace.

4.2. Basis of calculation:

4.2.1. Rate of melting:

a) On the basis of initial weight:

DRI dissolve in molten bath,

$$c = a - b \dots\dots\dots(1)$$

Where a and b are the original and final weight of sponge iron before and after melting at time t sec.

Amount of sponge iron dissolution, at t sec,

$$e = c / a \dots\dots\dots(2)$$

Hence, the rate of sponge iron dissolution,

$$S = de / dt \dots\dots\dots(3)$$

b) On the basis of fraction dissolved:

Melting rate (S1, gm / sec) will be determined by:

$$S1 = c / t \dots\dots\dots(4)$$

The simplified equation is

$$S2 = 0.06 S1 \dots\dots\dots(5)$$

c) On the basis of total melting of sponge iron:

Let total weight of sponge iron (m in Kg) melts in t1 min,

Then total melting rate (S3, Kg/min):

$$S3 = m / t1 \dots\dots\dots(6)$$

4.2.2. Iron yield:

Iron yield (%) can be calculated:

$$[\{ (Pb Mb) \times 100 \} / (Pa Ma + Pc Mc)] \dots\dots\dots(7)$$

Where, Pa, Pb and Pc are % of iron present in steel scrap, sponge iron and steel product respectively. Ma, Mb and Mc weight of steel scrap, sponge iron and steel product respectively.

[2]

4.3. Calculation:

Total metallic Fe added = 30kg

Phosphorous content in sponge iron = 0.096%

Hence, total weight of phosphorous in sponge iron = 30 * 0.96 g

$$= 28.8 \text{ g}$$

$$\approx 30 \text{ g}$$

Let metallization of sponge iron = 80%

And Fe (Total) = 92%

$$\begin{aligned}\text{So, Fe (Metallic)} &= (80 \times 92) / 100 \\ &= 73.6\end{aligned}$$

To get 30kg Fe (Metallic), amount of sponge iron required = $30 / 0.736$
 $\approx 40\text{kg}$

Molecular weight of phosphorous = 31

Molecular weight of O = 16

Molecular weight of P_2O_5 = 142

Molecular weight of 4CaO = 224

To remove 62gm of phosphorous, required amount of P_2O_5 = 142gm

To remove 1gm of phosphorous, required amount of P_2O_5 = $(142/30)$ g

To remove 30gm of phosphorous, required amount of P_2O_5 = $(142/30) \times 30\text{g}$
 $= 68.71$ g

P_2O_5 is present in the slag in the form of $4\text{CaOP}_2\text{O}_5$.

For 142gm of P_2O_5 we require 224g of CaO

Hence, for 68.71gm of P_2O_5 we require $(224 / 142) \times 68.71$ g of CaO
 $= 108.39\text{g}$ of CaO

Thus, with 30kg metallic iron, 108.39gm CaO was added.

For 30kg metal 5% synthetic slag was added, that is 1500 g synthetic slag.

Along with 1500 g synthetic slag 20% mill scale was added. (i.e. 300 g).

4.4. Experiment:

4.4.1. Heat-1:

A. Analysis of slag produced after addition of Calcium Aluminate:

Composition of Calcium Aluminate:

CaO – 75%

Al_2O_3 - 25%

Amount of synthetic slag added = 1500g along with 300g mill scale.

Table 4.3. Composition of slag produced after addition of Calcium Aluminate.

FeO	18.6%
SiO ₂	1.2%
CaO	60.3%
Al ₂ O ₃	18.2%
P ₂ O ₅	1.7%

B. Equivalent phosphorous present in 1.7% P₂O₅:

In 142g P₂O₅, 62g phosphorous is available.

In 1g P₂O₅, (62 / 142) g phosphorous is available.

In 1.7g P₂O₅, (62 / 142) * 1.7 g phosphorous is available.

$$= 0.742\text{g phosphorous.}$$

C. Total phosphorous removed:

0.742g phosphorous is removed by 100g synthetic slag.

So, for 1800g synthetic slag, amount of phosphorous removed is equal to

$$= 1800 * (0.742 / 100)$$

$$= 13.36\text{g}$$

Hence, in first heat 13.36g phosphorous has been removed after adding 1800g of synthetic slag.

D. Analysis of metal produced after addition of Calcium Aluminate:

The metal sample had been collected at 1602°C.

Final phosphorous content of steel is 0.05%, which has been calculated by spectro analysis.

E. Degree of dephosphorization:

$$\text{Degree of dephosphorization} = \frac{(\text{Initial P}) - (\text{Final P})}{(\text{Initial P})} * 100$$

$$= \frac{0.096 - 0.05}{0.096} * 100$$

$$= 47.92\%$$

4.4.2. Heat-2:**A. Analysis of slag produced after addition of Calcium Barium Aluminate:****Composition of Calcium Barium Aluminate:**

CaO – 35%

Al₂O₃- 25%

BaO – 40%

Amount of synthetic slag added = 1500g along with 300g mill scale.

Table 4.4. Composition of slag produced after addition of Calcium Barium Aluminate.

FeO	18.9%
SiO ₂	1.2%
CaO	27.6%
Al ₂ O ₃	17.65%
P ₂ O ₅	1.95%
BaO	32.2%

B. Equivalent phosphorous present in 1.95% P₂O₅:

In 142g P₂O₅, 62g phosphorous is available.

In 1g P₂O₅, (62 / 142) g phosphorous is available.

In 1.95g P₂O₅, (62 / 142) * 1.95 g phosphorous is available.

$$= 0.85\text{g phosphorous.}$$

C. Total phosphorous removed:

0.85g phosphorous is removed by 100g synthetic slag.

So, for 1800g synthetic slag, amount of phosphorous removed is equal to

$$= 1800 * (0.85 / 100)$$

$$= 15.3\text{g}$$

Hence, in first heat 15.3g phosphorous has been removed after adding 1800g of synthetic slag.

D. Analysis of metal produced after addition of Calcium Barium Aluminate:

The metal sample had been collected at 1607°C.

Final phosphorous content of steel is 0.044%, which has been calculated by spectro analysis.

E. Degree of dephosphorization:

$$\begin{aligned}
 \text{Degree of dephosphorization} &= \frac{(\text{Initial P}) - (\text{Final P})}{(\text{Initial P})} * 100 \\
 &= \frac{0.096 - 0.044}{0.096} * 100 \\
 &= 54.167\%
 \end{aligned}$$

4.4.3. Heat-3:**A. Analysis of slag produced after addition of Barium Aluminate:****Composition of Barium Aluminate:**

BaO – 75%

Al₂O₃ - 25%

Amount of synthetic slag added = 1500g along with 300g mill scale.

Table 4.5. Composition of slag produced after addition of Barium Aluminate.

FeO	18.3%
SiO ₂	2.1%
Al ₂ O ₃	24.2%
P ₂ O ₅	0.96%
BaO	54.3%

B. Equivalent phosphorous present in .96% P₂O₅ :

In 142g P₂O₅, 62g phosphorous is available.

In 1g P₂O₅, (62 / 142) g phosphorous is available.

In 0.96g P₂O₅, (62 / 142) * 0.96 g phosphorous is available.

$$= 0.455\text{g phosphorous.}$$

C. Total phosphorous removed:

0.445g phosphorous is removed by 100g synthetic slag.

So, for 1800g synthetic slag, amount of phosphorous removed is equal to

$$= 1800 * (0.455 / 100)$$

$$= 9.19\text{g}$$

Hence, in first heat 9.19g phosphorous has been removed after adding 1800g of synthetic slag.

D. Analysis of metal produced after addition of Barium Aluminate:

Initial phosphorous content in sponge iron is 0.092 wt. %

The metal sample had been collected at 1668°C.

Final phosphorous content of steel is 0.072%, which has been calculated by spectro analysis.

E. Degree of dephosphorization:

$$\begin{aligned}\text{Degree of dephosphorization} &= \frac{(\text{Initial P}) - (\text{Final P})}{(\text{Initial P})} * 100 \\ &= \frac{0.092 - 0.072}{0.092} * 100 \\ &= 21.74\%\end{aligned}$$

Degree of dephosphorization is very less in 3rd heat because. The operating temperature was high, while metal sample had been collected. Due to high temperature phosphorous from slag returned back to the steel since, dephosphorization is preferable at low temperature. Thus, we had conducted second test with Barium Aluminate as synthetic slag.

4.4.4. Heat-4:

Due to the above disadvantage of high operating temperature, in this heat the temperature was maintained at 1610°C.

A. Analysis of slag produced after addition of Barium Aluminate:

Composition of Barium Aluminate:

BaO – 75%

Al₂O₃ - 25%

Amount of synthetic slag added = 1500g along with 300g mill scale.

Table 4.5. Composition of slag produced after addition of Barium Aluminate (2).

FeO	19.3%
SiO ₂	1.9%
Al ₂ O ₃	23.9%
P ₂ O ₅	2.07%
BaO	52.7%

B. Equivalent phosphorous present in 2.07% P₂O₅:

In 142g P₂O₅, 62g phosphorous is available.

In 1g P₂O₅, (62 / 142) g phosphorous is available.

In 2.07g P₂O₅, (62 / 142) * 2.07 g phosphorous is available.

$$= 0.901\text{g phosphorous.}$$

C. Total phosphorous removed:

0.901g phosphorous is removed by 100g synthetic slag.

So, for 1800g synthetic slag, amount of phosphorous removed is equal to

$$= 1800 * (0.901 / 100)$$

$$= 16.27\text{g}$$

Hence, in first heat 16.27g phosphorous has been removed after adding 1800g of synthetic slag.

D. Analysis of metal produced after addition of Barium Aluminate:

Initial phosphorous content in sponge iron is 0.09 wt. %

The metal sample had been collected at 1610°C.

Final phosphorous content of steel is 0.04%, which has been calculated by spectro analysis.

E. Degree of dephosphorization:

$$\text{Degree of dephosphorization} = \frac{(\text{Initial P}) - (\text{Final P})}{(\text{Initial P})} * 100$$

$$= \frac{0.09 - 0.04}{0.09} * 100$$

$$= 55.55\%$$

Table 4.6. Chemical composition of Metal samples

Sample	Phosphorous
Sponge iron	0.09-0.096
1 st metal	0.085
2 nd metal	0.05
3 rd metal	0.044
4 th metal	0.04

Where,

1st metal = Metal after melting sponge iron in induction furnace with out addition of any external slag.

2nd metal = Metal after addition of Calcium Aluminate.

3rd metal = Metal after addition of Calcium Barium Aluminate.

4th metal = Metal after addition of Barium Aluminate.

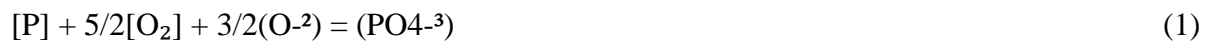
Chapter-5

RESULTS AND DISCUSSION

5.1. Results:

In primary steel making, oxygen is used as an agent for oxidation of dissolved impurities like C, Si, Mn and P. To some extent, iron itself is also oxidized during the process. The process is also known as oxygen steelmaking. On the other hand, in induction furnace steel making, no direct oxygen is introduced in the bath. The impurities are oxidized by introducing FeO in the bath. The requirement of FeO for slag formation and oxidation of various elements is fulfilled by addition of sponge iron. Thus, presence of FeO is important as it corresponds to oxygen potential of the slag.

Removal of phosphorous takes place by oxidation. The product, phosphorous pentoxide is being held by basic constituents, like CaO, present in the slag. In steel making processes basicity of the slag is maintained by addition of calcined lime. The reaction may be given by,



The oxidation reactions for other elements may be written as,



In the present work, dephosphorization experiments have been carried out as discussed in previous section. Total four heats were processed using, scrap and sponge iron. During each individual heat, the samples of slag and liquid metal have been collected. The results for metal and slag samples are given in Table 4.6 and 5.1 respectively. The results show chemical analysis of metal and slag samples. From the data it can be observed that degree of dephosphorization varies from 21.74% to as high as 55.55 % for various heats.

Borovsky [10] showed that phosphorous distribution ratio i.e. $(P_2O_5) / [P]$ or U_p required higher basicity's and FeO content, lower SiO_2 and Al_2O_3 , and very low P_2O_5 . However, FeO content in the slag is needed to be 15–35 % for effective dephosphorization. Another very important condition for dephosphorization is lowest possible temperature [11]. In IMF operation, slag is removed from furnace top. Many a times it is a manual process. Increase in basicity leads to increase in slag volume. Large slag volume makes IMF operation difficult. Moreover, upper surface of the slag remains in contact with atmosphere which decreases slag temperature. Hence the slag is continuously churned by rod from the top.

The favourable conditions for removal of Sulphur from steel bath are presence of reducing slag, high basicity and high temperature [12]. In the present work slag is oxidizing in nature as the minimum FeO content is about 16 %. Thus, present work maintains conditions for phosphorous removal.

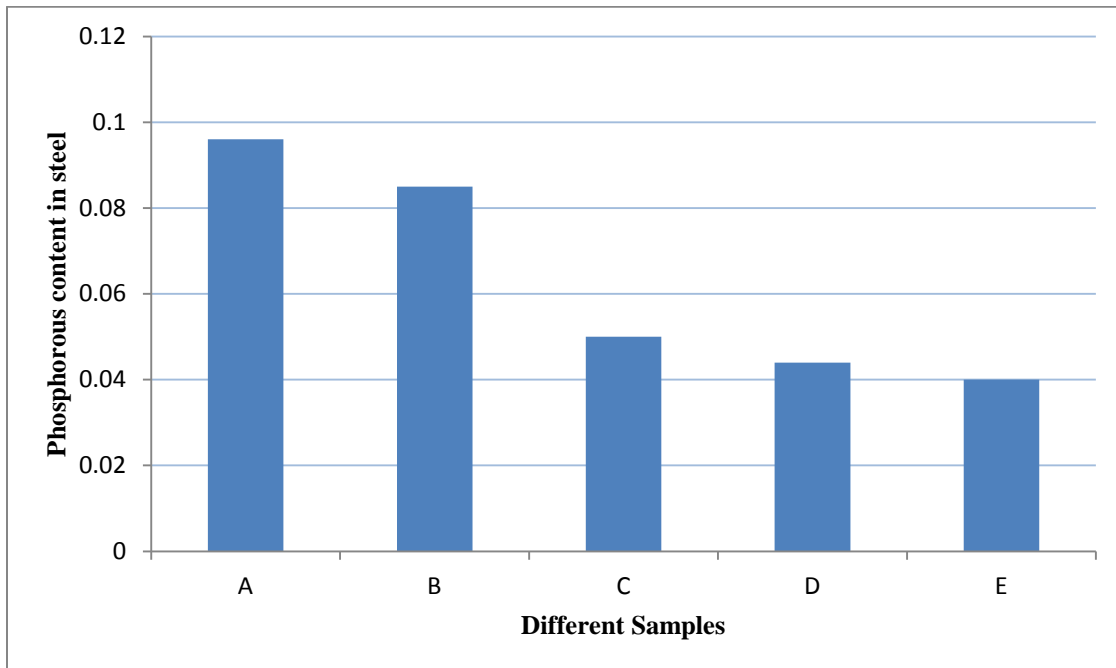


Figure 5.1. Phosphorous content of various samples

Where, A- DRI, B- Phosphorous in steel without double slagging, C- - Phosphorous in steel after deslagging with Calcium Aluminate, D- Phosphorous in steel after deslagging with Calcium Barium Aluminate, E- Phosphorous in steel after deslagging with Barium Aluminate

5.2. Discussion:

- It is possible to dephosphorizing the steel. For this double slagging method has to be adopted and lining has to be changed from acidic to basic or neutral.
- The temperature has to be closely monitored.
- Experiment shows that the best dephosphorization is obtained by addition of Barium aluminate, since the activity of Barium aluminate is more than Calcium Aluminate.
- When the temperature is beyond 1650°C the phosphorous may get back to the metal. This has been illustrated by conducting experiment at 1668°C with Barium Aluminate where degree of dephosphorization obtained is only 21.74%.

Table 5.1. Chemical composition of slag, operating temperature and their Degree of dephosphorization:

Heat	Sample	Phosphorous	P ₂ O ₅	Operation Temperature	Degree of dephosphorization
0	Slag-1	0.069		1630°C	--
1	Slag-2		1.70	1602°C	47.92%
2	Slag-3		1.95	1607°C	54.17%
3	Slag-4		0.96	1668°C	21.74%
4	Slag-4		2.07	1610°C	55.55%

Where,

- Slag-1 = slag which is produced after melting sponge iron
- Slag-2 = slag after addition of Calcium Aluminate.
- Slag-3 = slag after addition of Calcium Barium Aluminate
- Slag-4 = slag after addition of Barium Aluminate.

5.3. Limitations:

- The laboratory induction furnace did not provide for close temperature monitoring.
- We have conducted only one experiment with each of the fluxes, for a reproductive result number of experiments need to be conducted.

Chapter-6

CONCLUSIONS

6. Conclusions:

Though primary steelmaking is more popular than induction furnace steelmaking, the metallurgical aspects of the process are needed to be studied. Removal of Sulphur and phosphorous from steel in induction furnace route of steelmaking can be possible with neutral or basic lining. The stirring of the molten bath in induction furnace is also important.

The project establishes beyond doubt that it is possible to dephosphorizing steel produced from induction furnace route by,

- Closely monitoring the temperature.
- Double slagging has to be adopted.
- Changing the acidic lining of the furnace in to a more costly basic lining or at least to a neutral lining.
- Deslagging with the Barium Aluminate gives the best result concerning dephosphorization.
- Removal of phosphorous can be achieved by maintaining basicity and FeO in the slag.
- In the present work maximum 55.55% dephosphorization has been achieved.
- However before making a firm decision more number of experiment has to be conducted.

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